Soil compaction effects on grassland silage yields and soil structure under different levels of compaction over three years

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Title: Soil compaction effects on grassland silage yields and soil structure under different levels of compaction over three years.

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Application Text Abstract: Soil compaction has been estimated to be responsible for 33 million ha of soil degradation in Europe, reducing crop yields, however there is limited data on grassland silage yields loss. This work aimed at studying the effect of increased animal trampling and mechanical (tractor) soil compaction on grassland silage mean dry matter (DM) yields and soil structure over a three year period at two UK sites. Results showed trampling and tractor compaction decreased mean DM yields over three years and by the third year DM yield for the trampled area was 11.4% less on the soil with greater clay content soil and 12.0% less on the more sandier soil than the no compaction control. DM yield for the tractor compaction, by the third year, was 14.5% less than no compaction DM yield, on both soil types. Compaction reduced N uptake, decreased drainage and increased water filled pore spaces (WFPS). Linear regression of visual evaluation of soil structure (VESS) scores and bulk densities provided evidence that VESS is an effective tool for detecting grassland compaction and would assist with the management of moderately compacted soils where deteriorate soil conditions may result in yield loss.

Full Abstract: Soil compaction has been estimated to be responsible for 33 million ha of soil degradation in Europe, reducing crop yields, however there is limited data on grassland silage yields loss. Extended grazing periods, increased size and weight of farm vehicles and more extreme weather have fostered concern over the consequences of grassland management on reduced grass yield and soil quality. This work aimed at studying the effect of increased animal trampling and mechanical (tractor) soil compaction on grassland silage mean dry matter (DM) yields and soil structure over a three year period at two UK sites. These sites were on two established perennial ryegrass fields with contrasting soil textures; an imperfectly drained silty clay loam in SW Scotland and a well drained sandy loam from central England. Results showed trampling and tractor compaction decreased mean DM yields over three years and by the third year DM yield for the trampled area was 11.4% less on the soil with greater clay content soil and 12.0% less on the more sandier soil than the no compaction control. DM yield for the tractor compaction, by the third year, was 14.5% less than no compaction DM yield, on both soil types. Compaction treatments gave the greatest reductions for the first silage cut DM yields annually, for both soil types. The largest reductions (19.0% for trampling and 37.7% for tractor) were on the soil with the greater clay content in the second year, with the coolest start to the growing season. Compaction reduced N uptake, decreased drainage and increased water filled pore spaces (WFPS). Linear regression of visual evaluation of soil structure (VESS) scores and bulk densities provided evidence that VESS is an effective tool for detecting grassland compaction and would assist with the management of moderately compacted soils where deteriorate soil conditions may result in yield loss.

Keywords: Soil compaction, grassland, bulk density, yield, Visual Evaluation of Soil Structure

1. Introduction: Concerns about the structural damage of grassland soils by compaction have grown in recent years. Soil compaction has been estimated to be responsible for 33 million ha of soil degradation in Europe (Hamza and Anderson, 2003), with a more recent estimate that 32% of European subsoils were compacted and 18% were moderately susceptible to compaction (Horn and Fleige, 2009).

The potential for soil compaction and soil structural damage increases with soil moisture, up to field capacity, the optimum point for compaction and corresponds to the soil plastic limit (Hamza and Anderson, 2005). Pressure on the soil surface forces the soil aggregates closer together, deforming the structure and reducing the soil porosity resulting in an increase in soil bulk density. In turn, this restricts the diffusion of oxygen (O_2) and the hydraulic conductivity in the soil (Arvidsson and Hakansson, 1991; Batey, 2009). The increase in soil bulk density as a result of compaction also has been shown to alter and reduce root growth (Tracy et al., 2011; Botta et al., 2006; Głąb, 2013) and decrease the uptake of nutrients from the soil (Lipiec and Stępniewski, 1995; Arvidsson, 1999). These factors, in conjunction with increased soil moisture as a result of reduced drainage, can decrease the efficiency of the soil microbial population in the turnover of nutrients available to the crop (Cui and Holden, 2015). The effects of compaction on soil functions vary with soil type. Light sandy soils, due to their larger soil particles and larger pore size are less susceptible to compaction, even when moist, compared to silty clay loam soils with smaller particles and smaller pore size with a weaker structure that are therefore more compactible, especially when moist (Horn et al., 1995).

Soil compaction damage is becoming more common through the introduction of larger machinery (Gysi et al., 2000; Van den Akker and Schjønning, 2004). The more frequent occurrence of wetter weather conditions predicted, even during the summer months, in Europe (Christensen and Christensen, 2003), increases risks associated with soil structural damage through compaction.

Previous work has shown that compaction damage of soil under arable crops decreased crop yield of cereals (Radford et al, 2001), sugar beet (Koch et al, 2008) and forage maize (Nevens and Reheul, 2003) and increased the need for nitrogen (N) fertiliser to maintain the yields at pre-compaction levels (Soane and van Ouwerkerk, 1995).

The study of the effects of soil compaction on intensive grassland has not been as extensive as arable land (Douglas, 1997) or not based on temperate growing conditions (Balbuena et al, 2002). A recent visual survey of 300 grassland sites across England and Wales identified differing severities of structural damage with an estimated 10% of soils in poor condition (Defra, 2012; Newell-Price et al, 2013). This corresponded well with bulk density measurements that indicated 16% were badly compacted. However, if sites assessed as moderate soil condition, i.e. requiring management to alleviate the compaction problem, were considered, this resulted in approximately 70% of sites affected by soil structural damage.

This study also showed the suitability of visual evaluations of soil structure for quantifying structural damage to grasslands.

Two of the main causes of damage to grassland soils from compaction are trampling (Menneer et al., 2005; Thomas et al., 2008) by grazing animals and vehicle traffic (Batey, 2009). In recent years the more intensive and extended duration (i.e. February to October) of grazing in dairy farming (Kennedy et al., 2006) has encroached into periods when the soils are wetter and likely to be closer to field capacity (Defra, 2008), thus increasing the potential for intensively managed grassland to be damaged by soil compaction and potentially reduce yields through trampling (Herbin et al., 2011) and vehicle traffic. Quantifying yield loss from these two sources of compaction is important to help farmers in managing their soils to ensure they sustain maximum productivity.

The aims of this study were to investigate the effect of both animal trampling and vehicle compaction on grassland soil structure, yield reduction and grass sward quality of two contrasting soils (a coarse textured draining sandy soil and a finer textured, silty clay loam) in differing climates (both temperate but one cool and wet with the other warmer with less rainfall) over three consecutive years.

2. Materials and Methods:

2.1. Field experiment sites

The two sites were chosen to represent different climates and soil types within the UK with potentially contrasting responses to compaction. One site was located in the south west of Scotland (55^{o}02’19’’N, 3^{o}36’06’’W) (SRUC) and, although productive, was susceptible to poaching and compaction, particularly when wet. The field was an imperfectly drained silty, clay, loam of the Stirling soil series (30% clay, 14% sand and 55% silt) (Gleyic Cambisol, FAO, 2006) that overlies red sandstone parent material (pH 5.7, K and P medium to high) and had been sown as a perennial rye-grass sward (*Lolium perenne*) for 5 years prior to the experiment starting. The second site was located on the campus farm of Harper Adams University (HAU), Shropshire, central England (52º46’53’’N, 2º26’20’’W) on a freely draining sandy loam (> 20% sand and < 18% clay) of the Arrow soil series (Eutric Cambisol, FAO, 2006) with an underlying sandstone parent material (pH 7, K and P high). The field had supported a productive, sown perennial ryegrass sward for 3 years prior to the start of the experiment.

2.2. Experimental design and compaction treatments

The same randomised block experiment was established at each location and consisted of three replicate blocks (20 x 72m). Each block contained three replicate treatments (24 m x 20 m) of i) cattle trampling compaction, ii) weighted tractor compaction and iii) a control of no compaction. The trampling compaction was achieved by 12 heifers (target weight of 550 kg) walking across each of the three replicate treatment areas for one hour, on two occasions, one week apart. Mechanical compaction was performed by driving a weighted tractor (10.5 t) over the treatment areas so the wheeling tracks covered the entire sward surface. This was based on the width of the area needing to be covered and the wheeling width of 1.7 m of the tractor. The tractor drove up the plot with the outside of the rear tyre corresponding to the plot edge then turning off the plot and returning with the rear tyre abutting the edge of the first wheeling. This process was repeated until the whole of the area was covered. The target compaction pressures of animal hoof and mechanical wheel were designed to be similar at ~250 kPa, to allow the influence of the mechanism of compaction to be distinguished from that of the compactive effort. The no compaction areas only had essential traffic for the management of the grass sward for three silage cuts (i.e. harvesting, fertiliser and slurry application). As the main treatment areas contained other sub-treatments, therefore smaller areas (4 m x 20 m) were used for sampling. The effects of compaction on yield were only considered in this study from the plots that had not had any further treatments. Soil measurements were taken from one half so not to disturb the yield taken from the other half. The layout of the experimental plots is shown in the Supplementary Data.

The first compaction treatments were imposed in November 2011 at SRUC (i.e. the autumn before yield measurements) and February 2012 at HAU (i.e. the same year as yield measurements). These were repeated at a similar time each year for a further two years (Table 1).

Fertiliser was applied three times during the year (Table 1), once as an inorganic fertiliser (urea at 60 kg N ha^{-1}) at the end of March, with slurry subsequently (at a rate of 30 m^3 ha^{-1}; average N 63 kg ha^{-1}; P 13 kg ha^{-1}, K 49 kg ha^{-1}) with a tractor, tanker and trailing shoe within two weeks of the first and second grass cuts.

2.3. Measurements

2.3.1. Bulk density and Water Filled Pore Space

At SRUC, bulk density and gravimetric moisture contents were measured (Robertson et al, 1999) for all plots one week prior to application of any of the compaction treatments using cores sampled from metal rings (5 cm deep with a diameter of 7.3 cm) and then in October each year after before the subsequent compaction treatments were applied. Five samples for soil moisture, from each plot were taken during each sampling at the 0-10 cm and 10-20 cm depths. Three samples were taken at four sampling depths 0-5 cm, 5-10 cm, 10-15 cm and 15-20 cm for bulk density. Bulk density samples from 0-10 cm and 10-20cm were taken at HAU prior to the start of the experiment but only to 0-10cm depth after application of the compaction treatments, as the drier, stony ground conditions prevented obtaining deeper cores.

The water filled pore space (WFPS) (%) values were calculated using bulk density and water content data (Robertson et al, 1999) for monthly soil samples taken at 0-10 cm and 10-20 cm depths where data was available, assuming a general particle density of 2.65 g cm^{-3} (Blake and Hartge, 1986).

2.3.2. Visual Evaluation of Soil Structure (VESS)

Initial visual assessments of soil structure were made throughout the experiment, one week before the compaction treatments were applied, using the Visual Evaluation of Soil Structure (VESS) system (Ball et al, 2007). This involved digging out one intact block of soil (25 x 10 x 15 cm) from each plot and scoring the structure for attributes of strength, porosity and aggregate morphology each sampling time. The VESS assessment was repeated within each treatment block after the initial compaction treatments were applied and again on all replicate treatments in October of 2012, 2013 and 2014, before further compaction treatments were applied. Initial VESS assessments were done at HAU a week before the first compaction treatments were applied in February 2012 and were repeated for all the replicate treatments at the end of each growing season either at the end of September or beginning of October 2012, 2013 and 2014.

2.3.3. Grass sward (perennial ryegrass) yield and quality

Grass yield data were collected from three cuts during the year, approximately early May, July and the end of August or early September (Table 1), from a strip (1.45m x10m) down the centre of the half of the plot (4m x 10m) reserved for yield measurements. These were taken using a Haldrup harvester (Haldrup Ltd, Germany). Grass yield was calculated from the fresh weight of the cut strip and a dry matter (DM) result taken from a grab sample of the fresh off-take from the plots. Analysis of the grass quality was done on separate sub samples of the fresh grass for crude protein (CP) (Kjeldahl digestion and analysis using the Gerhardt Vapodest system; calculated as N x 6.25) , ash (MAFF/ADAS RB427), modified acid detergent (MAD) fibre (Clancy and Wilson, 1966), metabolisable energy (ME) and digestibility (D). The herbage N contents for each silage cut at the two sites were calculated from the N concentration and the DM yields (O'Connor et al, 2012):

2.3.4 Weather data

Weather data were collected daily at 09:00hrs GMT at 1000m to the northeast of the experimental field at SRUC and 500m to the east of the experimental field at HAU (Table 2).

2.3.5 Statistical analysis

Data were analysed using Genstat version 16 (VSN International, Hemel Hempstead). The trampled, tractor and no compaction treatments for bulk density, VESS, WFPS, DM yield, crop N content were analysed on a randomised basis using Genstat ANOVA on normally distributed data (tested with Shapiro-Wilks) within each year. Year was included as a factor for bulk density, VESS, WFPS, yield and N content and treatment x year significance assessed. Any significance was investigated with a post hoc Tukey's test at a level of significance of $P<0.05$. Analysis was done separately for each experimental site. Linear regression analyses ($P<0.05$) were performed to determine relationships between the mean annual VESS and mean soil bulk density for the two experiments using Genstat V16 linear regression analysis.

3. Results

3.1. Soil bulk density

At SRUC the compaction treatments increased mean soil bulk densities (0-10 cm) over the three years (Figure 1a) by 130 kg m^{-3} for the trampled ($P<0.01$) and 210 kg m^{-3} for tractor compaction ($P<0.001$) compared to the no compaction. Over the same period (October 2011 to October 2014) the no compaction control treatment mean bulk densities showed an 80 kg m^{-3} decrease at 0-10 cm and gave similar values for 10-20 cm.

There were differences in mean bulk densities between treatments at SRUC each year at 0-10 cm soil depth but only in October 2013 at 10-20 cm depth when the trampled treatment increased by 8.4% ($P<0.01$) and the tractor increased by 9.4% ($P<0.01$) compared to the no compaction (Figure 1b). In the final mean soil bulk density measurements (October 2014) at 0 -10 cm, values had increased for the trampled by 18.2% ($P<0.01$) and by 23.2% ($P<0.01$) for the tractor compaction, compared to the no compaction.

At HAU 0-10 cm depth, mean soil bulk densities did not change significantly over the three years of the experiment (Figure 1a), although values increased in the compaction treatments compared to a decrease in the no compaction treatment.

3.2. Water Filled Pore Space

At SRUC 0-10 cm soil depth, the annual mean WFPS values for no compaction were significantly lower than the corresponding trampled ($P<0.01$) and tractor compacted soils ($P<0.001$) during 2012 (Table 3). This trend continued through 2013, with a lower mean WFPS for the no compaction treatment ($P<0.001$) compared with both compaction treatments. Again in 2014 the trampled ($P<0.05$) and tractor ($P<0.01$) compaction WFPS values were significantly higher than those for the no compaction treatment.

At 10-20 cm soil depth, at SRUC, the annual mean WFPS values showed a similar pattern to the 0-10 cm depth, with the compaction treatments having significantly greater WFPS values during 2012 and 2013 compared to the no compaction control. There was no significant compound affect of year on WFPS for either soil depth.

3.3. Visual Evaluation of Soil Structure (VESS)

At SRUC the mean VESS scores (Sq) (Figure 2) were generally greater (poorer soil structure) than at HAU and followed a similar pattern to the soil bulk density measurements, with tractor compaction showing a year on year increase after each subsequent compaction event. Over the three years the mean Sq increased by 0.81 ($P<0.001$) for the trampled treatment and increased by 1.44 ($P<0.001$) for the tractor compaction, compared to the control.

At HAU, the mean Sq remained similar under the trampled compaction with only a 0.28 increase, however, the tractor compaction increased by 1.02 ($P<0.05$), after the second compaction event in February 2013.

3.4. Silage dry matter yields

The SRUC trampling and tractor compaction treatments gave 8.4% and 10% reductions in overall mean DM yields (Figure 3), respectively, for all cuts over all three years compared to no compaction. At HAU, mean DM yields over the three years for all cuts were also decreased by 7.2% for trampling and by 4.8% for the tractor compaction, compared to the no compaction (Figure 3). There was a Year effect at SRUC ($P<0.001$) with greater variability in yield year on year and 2014 provided significantly greater yields for trampled, tractor and no compaction compared to 2012 and 2013 but not at HAU where only the no compaction was significantly greater in 2014 ($P<0.01$) and in the all years combined ($P<0.05$).

At both sites the compaction treatments reduced the first silage DM yields the most, although not always significantly (Figure 4). The SRUC mean DM yield reductions for the trampling treatment, compared to the no compaction, were 16.3% ($P<0.01$), 19.0% ($P<0.05$) and 10.3% ($P<0.01$) for 2012, 2013 and 2014, respectively (Figure 4). The mean DM yield reductions for the tractor treatment were 15.0% ($P<0.01$), 37.7% ($P<0.001$) and 15.2% ($P<0.01$) for 2012, 2013 and 2014, respectively. The first silage cut mean DM yields at HAU followed a similar pattern over the three years. These were reduced by 13.1% ($P<0.001$), 6.6% and 9.7% for 2012, 2013 and 2014, respectively for the HAU trampling compaction (Figure 4). The tractor compaction reduced mean DM yields, in the first cut, for 2012 and 2014 by 7.4% and 14.9%, respectively, with no reduction for 2013.

At the second silage cut at SRUC, during 2012, the mean yields of the compaction treatments exceeded those of the no compaction treatment by 15.7% ($P<0.01$) for trampling and 23.5% ($P<0.001$) for tractor compaction, respectively, with smaller increases during

2013. Mean yields of the second cut silage increased at HAU during 2013 for the tractor compaction by 15.3% ($P<0.05$). There was a year effect for the second silage cut at SRUC, especially for the compaction treatments ($P<0.01$), whereas the no compaction produced similar yields during 2012 and 2013. The effect of year was less at HAU with trampled compaction being most significantly different ($P<0.01$).

The compaction treatments reduced mean yields from the second cuts at both sites during 2014 with 34.2% ($P<0.05$) for the trampling and 35.6% ($P<0.05$) for the tractor compaction at SRUC and 23.1% ($P>0.05$) for the trampling and 16.9% ($P>0.05$) for the tractor compaction at HAU.

During 2012 and 2013 the third cuts at SRUC gave smaller mean yield reductions as a result of compaction. However, the yields were similar for all the treatments during 2014. This pattern was not seen at HAU where the compaction continued to reduce mean DM yields by10.0% for trampling and 19.3% for tractor compaction, although not significantly. Year on year changes were the least for the third cut yields at both sites, with only the compaction treatments providing a significant reduction during 2012 at SRUC.

3.5. Herbage N content

At SRUC the mean content of 1st cut herbage N over the three years was significantly greater in the trampled ($P<0.05$) and tractor ($P<0.01$) compaction treatments than for the no compaction (Figure 5). During 2012 the compaction treatments gave a significantly reduced mean herbage N content compared to the no compaction: tractor (107 g kg^{-1} less ($P<0.05$)) and trampling (113 g kg^{-1} less ($P<0.05$)).

However, no compaction at SRUC produced consistently greater mean herbage N contents than the compaction treatments for all the other silage cuts during the experiment, but these were only significant for the first silage cut for tractor compaction ($P<0.05$) in 2013 and 2014.

HAU mean herbage N contents for the three silage cuts over the three years were greater than those at SRUC with more significant differences between treatments (Figure 5). The no compaction mean herbage N content was also significantly increased compared to the trampling treatment in the second ($P<0.01$) and third ($P<0.05$) silage cuts during 2014. A Year effect was seen for all three silage cuts at both SRUC ($P<0.001$) and HAU ($P<0.001$). These effects followed a similar pattern to the DM yield, especially with the increase at both sites for the 1st cut herbage N.

3.6. Regression analysis of VESS and bulk density

When the annual mean VESS scores for each experiment across the three years were compared with the annual mean soil bulk densities, there were significant linear regressions for both experiments (Figure 6). There was a stronger linear increase for SRUC $R^2 = 0.97$ ($P<0.001$) than for HAU $R^2 = 0.37$ ($P<0.05$).

4. Discussion

The SRUC soil, with the greater clay content, showed the largest increase in mean soil bulk density after the first compaction treatments (November 2011). This accounted for 64% of the overall bulk density increase between October 2011 and October 2014, and agreed with other research (Taylor et al, 1982; Bakker and Davis, 1995) that showed up to 75% of soil compaction was the result of the first application of a repeated compaction treatment. It was surprising that the animal trampling increased soil compaction at 10 – 20 cm on the more clay soil, as it was assumed that this compaction would predominantly affect the upper 10 cm due to the smaller area of application due to the heifers' foot area but similar pressures over a larger area for the tractor weight. Although, over the three years, the increase in soil bulk density was much less for the trampling (a 5.8% increase to 1280 kg m^{-3}) than for the tractor compaction (a 9.7% increase to 1340 kg m^{-3}; $P<0.05$) at the 10-20 cm soil depth. The increase in bulk density, at SRUC, for the tractor compaction at the 10-20cm soil depth was split between the first (40%) and second (47%) compaction events and indicated that repeated applications were needed to increase the density of the soil at this depth.

The reduction in bulk density, at both SRUC and HAU, over the three years for the no compaction control was (Figure 2) attributed to wetting and drying and freeze/thaw processes improving soil structure with soil contraction and expansion increasing porosity (Parker et al, 1982; Unger, 1991; Jabro et al, 2014). This reduction in soil bulk density was thus perhaps a result of the natural recovery of the soil from any compaction that had started before experimentation with careful reduction of any compaction treatment during the experiment.

The soil type at the HAU site contained a greater proportion of sand compared to the SRUC soil (over 18% at HAU compared to less than 14% at SRUC). Previous work has shown that sandy soils are more difficult to compact, as a result of the larger particle size (Bodman and Constantin, 1965; Keller and Håkansson, 2010). Nevertheless, there was still an increase in bulk density of 8% in the trampled treatment and of 6% for the tractor compaction at HAU, with a progressive decrease in structural quality over the three years of the experiment. Most of the bulk density increase at HAU occurred with the second and third compaction treatments, indicating the greater resistance to compaction of the sandier soil compared to the greater clay content soil at SRUC.

The mean WFPS values of ~ 100% for the compacted areas after high rainfall are an indication of the observed poor drainage due to the persistence of saturation, with pools of surface water ponding. The increased WFPS values down to 20 cm depth for both the trampled and tractor compaction indicated that the compaction was affecting porosity and hence the drainage down to this depth. The blocks of soil extracted for the VESS assessment of soil structure each October after compaction revealed obvious signs of poor drainage from the SRUC site with orange mottling coating root or worm channels, caused by oxidised iron deposits. Large, angular soil aggregates in the top 0-10 cm of the trampled soil and later to 20 cm in tractor compacted soil were visible and were symptomatic of poor soil quality. However, the no compaction treatment revealed a more friable, crumbly soil structure with small (approximately 2 cm diameter), rounded soil aggregates. Such soil structure would allow water to drain freely and would unlikely to be improved further by management intervention. The reductions in mean DM yield were influenced by the decrease in soil structural quality from compaction (Bouwman and Arts, 2000) and the increased WFPS (Schulte et al., 2012).

The reductions in mean DM yield by compaction increased in general for both the experimental sites over the three years and by the third year the loss of DM yield was 11.4% for the trampling on the soil with the greater clay content and 12.0% on the sandier soil. The loss of mean DM yield from the tractor compaction was similar at both sites by the third year (14 - 15%). This indicated that soil type became less important as the accumulation of compaction increased. Balbuena et al. (2002) however, found larger grass yield reductions than those typically found in this study (40.3%) after one pass of a heavy (4200 kg) tractor on a fine clay loam soil, however, the tractor weight used was approximately 4 times greater than used in the current study.

The tractor compaction gave the greatest reduction in first cut mean DM yield in 2013 and 2014 at SRUC but the trampled treatment gave the greater mean DM reduction for 2012. This latter reduction was unexpected as the greater compaction of the tractor was expected to reduce yield more, however, poaching was observed for the trampling compaction treatment as the soft surface soil was displaced up and around the heifers' feet as they moved across the pasture. Pande (2002) had found a reduction of 43% DM from a severe trampling event in the previous autumn due to damage of the grass tillers from trampling.

The increase in mean WFPS to > 70% by compaction, especially for extended periods of time, would have made the microbial population more anaerobic, with reduced efficiency in nutrient provision for the growing crop. This includes organisms that mineralise the applied organic fertiliser (Beylich et al., 2010).

The cooler weather in early 2013 (Table 2) most likely reduced yields at both SRUC and HAU (Figure 3), with the first cut DM yield being significantly reduced for SRUC (Figure 4). This indicated a compounding effect of soil compaction with weather conditions during early season growth.

Increases in the second silage cut mean DM yields in the compaction treatments at both SRUC and HAU, during the first two years of the experiments (2012 and 2013) were unexpected. These mid-season recoveries in yield could be explained by two factors. First, restriction in growth by compaction up to the first silage cut would result in lower soil nutrient use efficiency than by the no compaction sward and therefore more nutrients would have been available for growth up to the second cut for the compacted treatments. Second, the physical constraints of the compacted soil would be less effective as the growing season progressed and the soils became drier and warmer. This recovery of the second silage cut yield has been observed in a previous study by Douglas (1997) who attributed it to improved water retention in the compacted soil enabling better soil water supply in the drier parts of the growing season and to larger reserves of nutrients being available due to the reduction in leaching of these compared to a more porous less compacted soil.

Significant positive linear regressions between the number of days before ≤2mm of rain fell after the first silage cut and the ratio of the compacted yield to no compaction yield for both the trampled (R^2=0.93; P<0.03) and tractor treatments (R^2=0.97; P<0.01) were seen for the more clay soil at SRUC. This increased yield from compacted soils for second cut silage was also found by Douglas (1997), who suggested the reduced soil porosity retained more water and reduced the loss of potential mineralisable nutrients from the top layer of the soil. These nutrients were then available for the grass roots and produced the increased yield compared to an uncompacted soil. However, there were negative regressions in the same parameters for the sandier, more well drained, soil at HAU, for both the trampled (R^2=0.97; P<0.01) and tractor compaction (R^2=0.96; P<0.02) indicating the soil water and nutrients drained away more easily; even with increased compaction. The sooner the rainfall after the first cut, the more likely these nutrients are to be leached. Nevertheless, by the third year of the experiment the effect of the soil compaction had now become apparent in the reduction in the second silage cut mean DM yields, especially at SRUC. This indicated that the accumulated compaction damage to the soil structure from 2011/2012 to 2014 appeared to have produced a progressive effect on reducing DM yield and the advantage of compaction retaining soil water and nutrients for the second silage cut had been lost.

The increased mean herbage N content at HAU compared to SRUC was an effect of both a greater off-take of herbage and higher crude protein content, as a consequence of the soil with the greater sand content at HAU provided overall better growing conditions.

The lower uptake of N in the herbage of the compaction treatments for the majority of the silage cuts at both sites was expected as the N content was linked to overall off-take and there was less herbage on the compacted treatments. A greater mean N content in the herbage did indicate a greater mean N content in the herbage may be the consequence of a greater efficiency in N usage and uptake from the soil, especially under the no compaction. As the same amount of N was applied to all three treatments, reduced uptake of N in the compaction treatments indicated that more N remained in the soil after cutting, with the potential for diffuse pollution through run off and leaching (Di and Cameron, 2002).

Increased soil bulk density and a change in a visual soil evaluation score, indicative of poorer structure, have been shown to be positively correlated in previous work (Newell-Price et al., 2013; Mueller et al., 2013). This was also the case in both the current experiments for the mean VESS score for the top 10cm and the mean soil bulk density, over the three years (Figure 6). However, the linear regression for the top 10 cm in the more clay soil at SRUC was much stronger (R^2=0.97 ($P<0.001$)) than the sandier soil at HAU (R^2=0.37 ($P<0.05$)) and would indicate levels of compaction that corresponds more closely with bulk density. This would allow VESS to be used to indicate levels of compaction, however, the relationships would be dependant on the type of soil.

Newell-Price et al (2013) surveyed soil structural conditions in English and Welsh grasslands and found strong correlations between the scores of the two visual assessment methods used, the visual soil assessment (vsa) method from New Zealand (Shepherd, 2009); the Peerlkamp (soil structure – 'St') method (Peerlkamp, 1967) and the bulk density in the top 10 cm of the soil. Both of these visual assessment methods have similar criteria to VESS.

Newell-Price et al (2013) estimated that approximately 8 to 12% of the grassland soils surveyed were in a poor condition and would have resulted in an obvious reduction in grassland yield. A further 54 to 63% of the grassland swards surveyed had soil in a moderate condition that was deemed likely to have reduced yield. The bulk density values and VESS scores of the compaction treatments in these experiments, especially after three years of compaction treatments would correspond to the moderate conditions of Newell-Price et al (2013). The estimation that about 2 to 3 million ha of grassland in England and Wales were only in a moderate condition would equate to a loss in DM yield of between 5.6 and 8.4 Mt from trampling and 6.0 and 9.0 Mt from tractor traffic depending on the soil type, based on the losses seen from the experiments described here.

5. Conclusions

Damage to soil structure through compaction reduced the yields of grassland swards that were affected by both animal trampling (between 11.4 and 12.0%) and by mechanical (tractor) compaction (14.5% reduction) after three years of these treatments. Soil WFPS was increased by the compaction treatments with soils being less free draining. The soil type contributed towards yield losses with a finer textured soil with a greater clay content showing a greater loss from tractor compaction during cold wet weather than a more easily drained sandier soil. Both soil types showed the greatest DM yield reductions for the first silage cut especially when there had been colder, wetter weather during the initial growing period. As the herbage N content of the swards decreased with increased compaction there was the potential for increased N loss through the soil and less efficient use by the crop. Close linear regressions were seen between the soil visual assessment method and the physical measurements of soil bulk density indicating the potential for the VESS method to be used as a management tool to assess the level of compaction in grassland and indicate the correct management to rectify soil structure and thereby increase DM yield.

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Table 1. Timings of compaction treatments, grass silage cuts and fertiliser applications for SRUC, Dumfries and HAU, Newport (numbers in brackets refer to the silage cut).

Treatment	Experimental Site	
	SRUC	HAU
Compaction	November 2011	February 2012
	November 2012	February 2013
	November 2013	February 2014
Urea application	Late March 2012	Early April 2012
	Mid March 2013	Early April 2013
	Late March 2014	Mid March 2014
Slurry application	Late May 2012	Late June 2012
	Mid July 2012	Late August 2012
	Mid June 2013	Late May 2013
	Late July 2013	Mid July 2013
	Mid June 2014	Mid May 2014
	Mid April 2014	Late June 2014
Silage cutting	Mid May 2012 (1)	Late May 2012 (1)
	Late June 2012 (2)	Late July 2012 (2)
	Early September 2012 (3)	Late September 2012 (3)
	Late May 2013 (1)	Late May 2013 (1)
	Mid July 2013 (2)	Early July 2013 (2)
	Early September 2013 (3)	Late August 2013 (3)
	Early June 2014 (1)	Mid May 2014 (1)
	Mid July 2014 (2)	Late June 2014 (2)
	Early September 2014 (3)	Mid August 2014 (3)

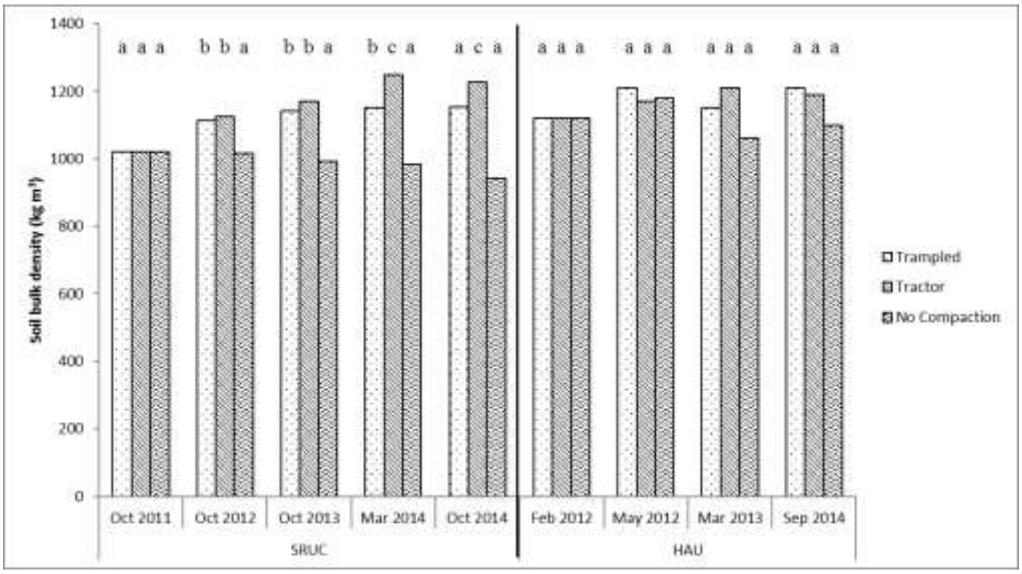
Table 2. Mean annual air temperature (°C) and mean and yearly total rainfall (mm) for SRUC and HAU for the three years of the experiment and mean temperatures (°C) and rainfall (mm) split into growing periods for the grass silage.

Year		Month				
SRUC		**Jan-April**	**May-July**	**Aug-Sep**	**Oct-Dec**	**Annual mean**
Air Temp mean (°C)	**2012**	6.5	12.8	14.0	6.3	9.9
	2013	4.4	14.2	14.3	8.1	10.3
	2014	7.0	14.6	14.7	8.1	11.1
Long-term mean*		**5.7**	**13.3**	**14.1**	**6.9**	**10.0**
HAU						
Air Temp mean (°C)	**2012**	6.3	13.9	14.7	6.8	10.4
	2013	4.3	13.7	14.8	8.4	11.3
	2014	7.6	15.3	14.9	8.3	11.5
Long-term mean*		**7.7**	**17.0**	**14.7**	**6.9**	**11.6**
SRUC		**Jan-April**	**May-July**	**Aug-Sep**	**Oct-Dec**	**Annual total**
Rainfall total (mm)	**2012**	227.8	368.4	275.4	486.6	1358.2
	2013	285.9	256.6	138.2	471.2	1151.9
	2014	428.8	176.3	119.9	536.9	1261.9
Long-term mean*		**347.1**	**213.9**	**183.8**	**376.1**	**1120.9**
HAU						
Rainfall total (mm)	**2012**	275.2	298.1	188.5	256.3	1018.1
	2013	190.4	198.6	158.1	193.2	740.3
	2014	276.4	181.7	100.2	217.8	776.1
Long-term mean*		**190.9**	**160.8**	**116.6**	**191.6**	**659.9**

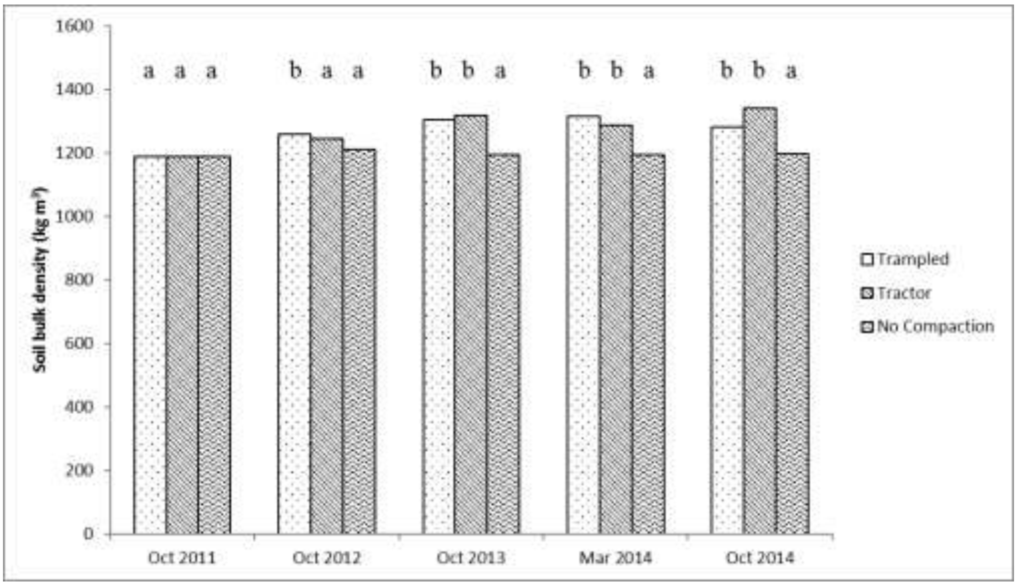
*Long-term mean 1981-2010

Table 3. Mean annual water filled pore space (%) values for the no compaction and compaction treatments (Trampled and Tractor compaction) for 2012, 2013 and 2014 at SRUC (values in brackets s.e.d. for compaction treatment compared to no compaction).

	No Compaction	**Trampled**	**Tractor**	**P value**	**No of reps**
0-10cm					
2012	71.1	82.8 (3.12)	88.7 (3.53)	<0.001	9
2013	74.7	90.1 (3.49)	93.4 (3.77)	<0.001	3
2014	67.8	86.4 (8.57)	91.2 (8.18)	0.01	3
10-20cm					
2012	74.6	81.3 (8.18)	86.4 (2.47)	<0.001	9
2013	75.0	84.2 (2.71)	86.7 (2.80)	<0.001	3
2014	69.5	79.2 (6.09)	83.3 (7.19)	0.07	3



a) SRUC and HAU (0-10cm soil depth)



b) SRUC (10-20cm soil depth)

Figure 1. Mean bulk densities (g cm^{-3}) for the no compaction, trampled and tractor compaction treatments at a) SRUC and HAU at 0 – 10 cm depth and b) SRUC at 10 – 20 cm, between 2011 and 2014. Letters indicate significant differences (P < 0.05) between means (each site analysed separately).

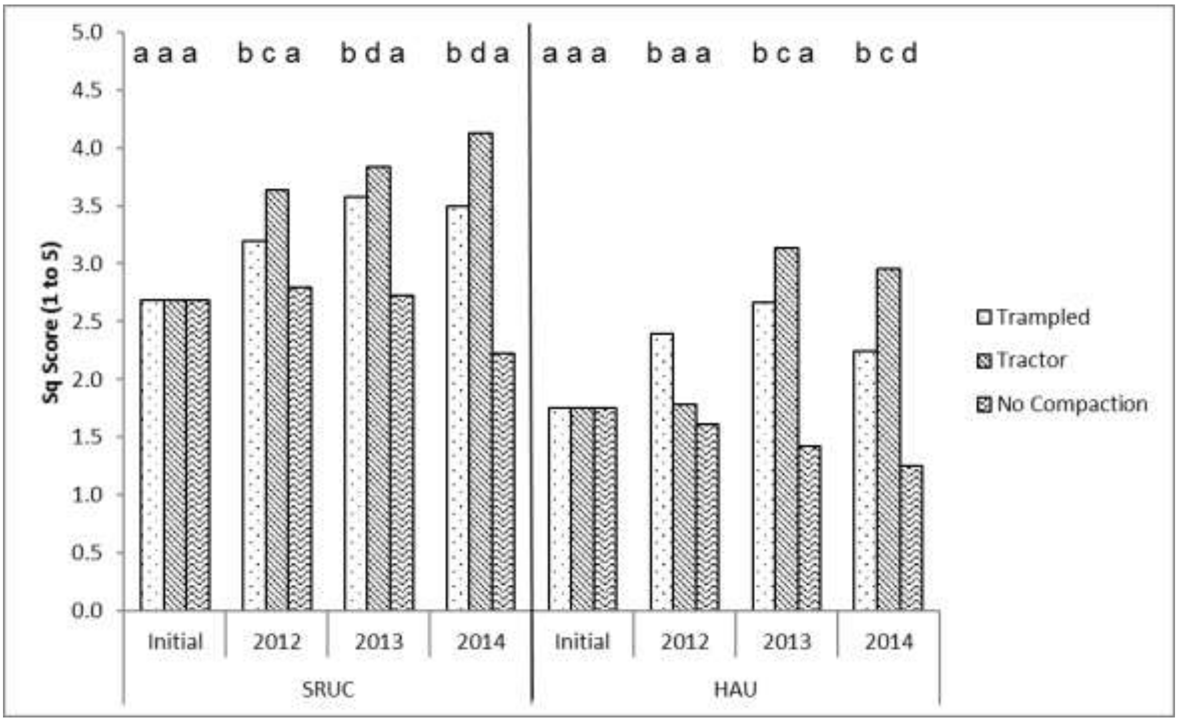


Figure 2. Mean Visual Evaluation of Soil Structure (VESS) scores (Sq Score 1 to 5) from initial pre-treatment soils and post-compaction treatment soils (trampled, tractor and no compaction) for SRUC and HAU. Letters indicate significant differences (P < 0.05) between means (each site analysed separately).

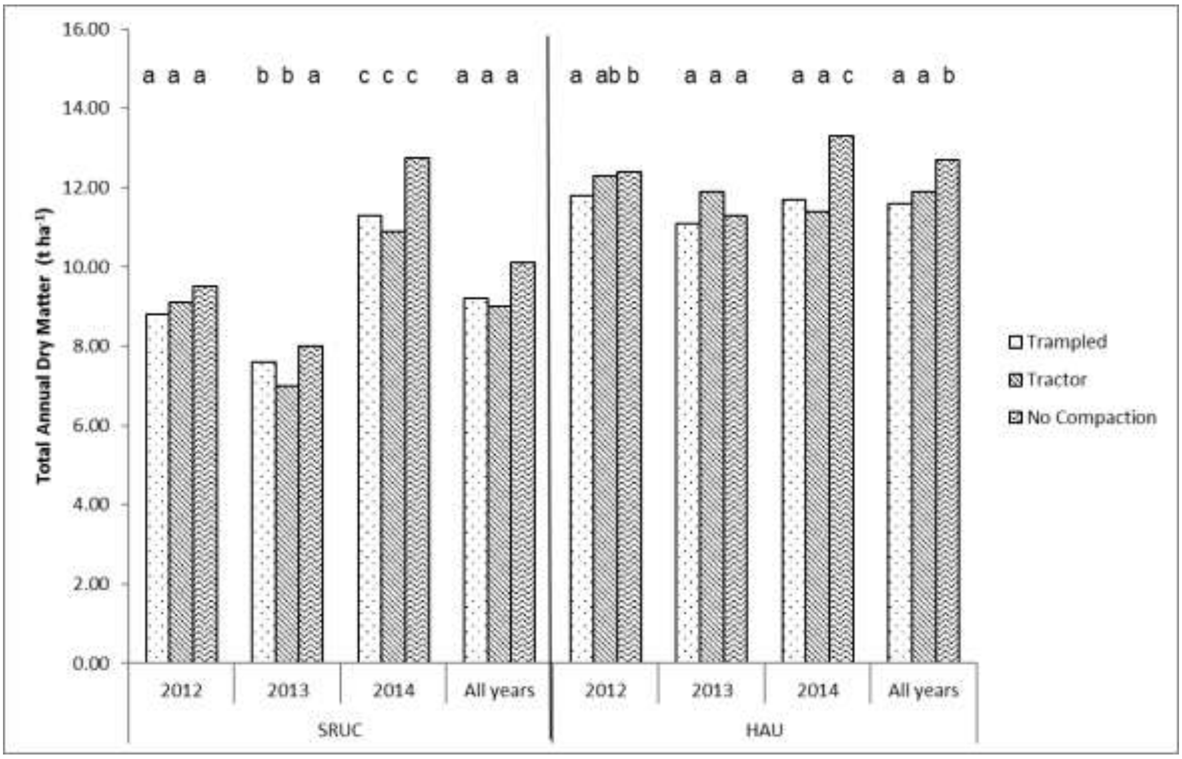


Figure 3. Annual and all-year means of combined silage dry matter yields (t ha^{-1}) from the no compaction, trampled and tractor compaction treatments from SRUC and HAU for the years 2012 to 2014. Letters indicate significant differences (P < 0.05) between means (each site analysed separately).

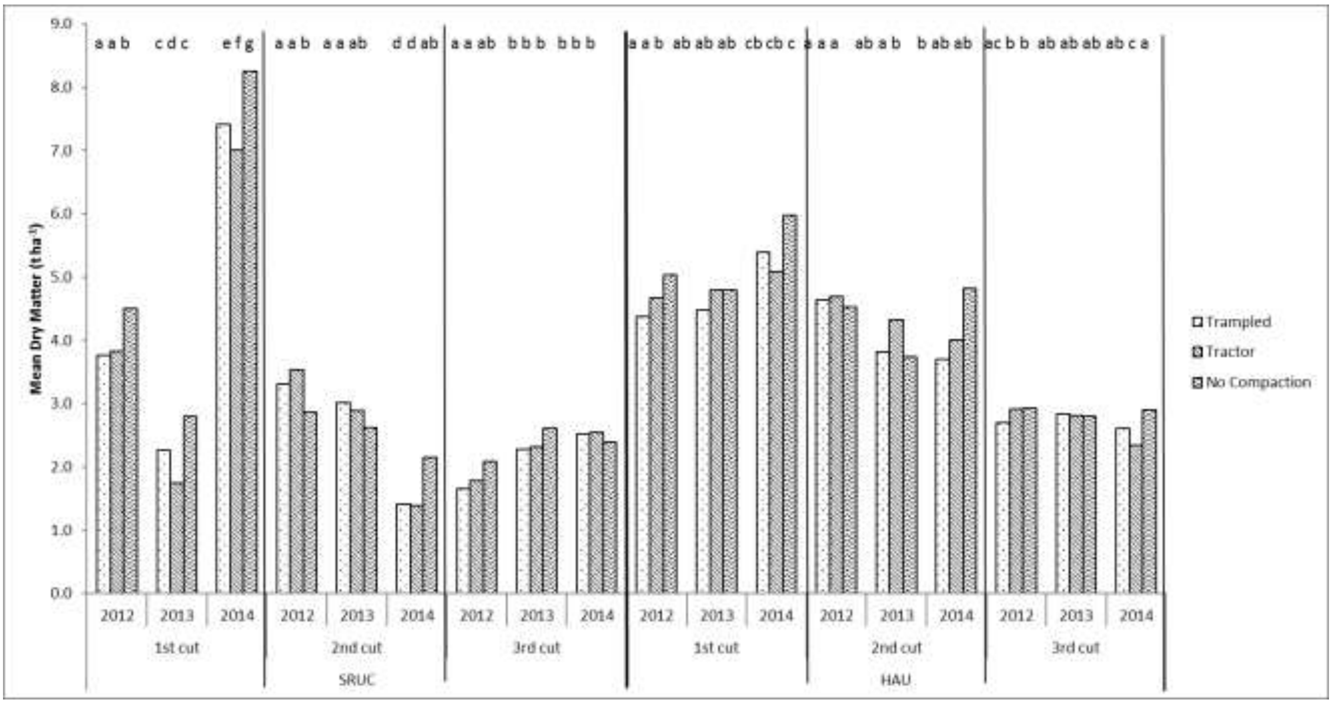


Figure 4. Mean silage dry matter yields (t ha^{-1}) for individual cuts from the no compaction, trampled and tractor compaction treatments from SRUC and HAU for 2012, 2013 and 2014. Letters indicate significant differences (P < 0.05) between means within each silage (each site analysed separately).

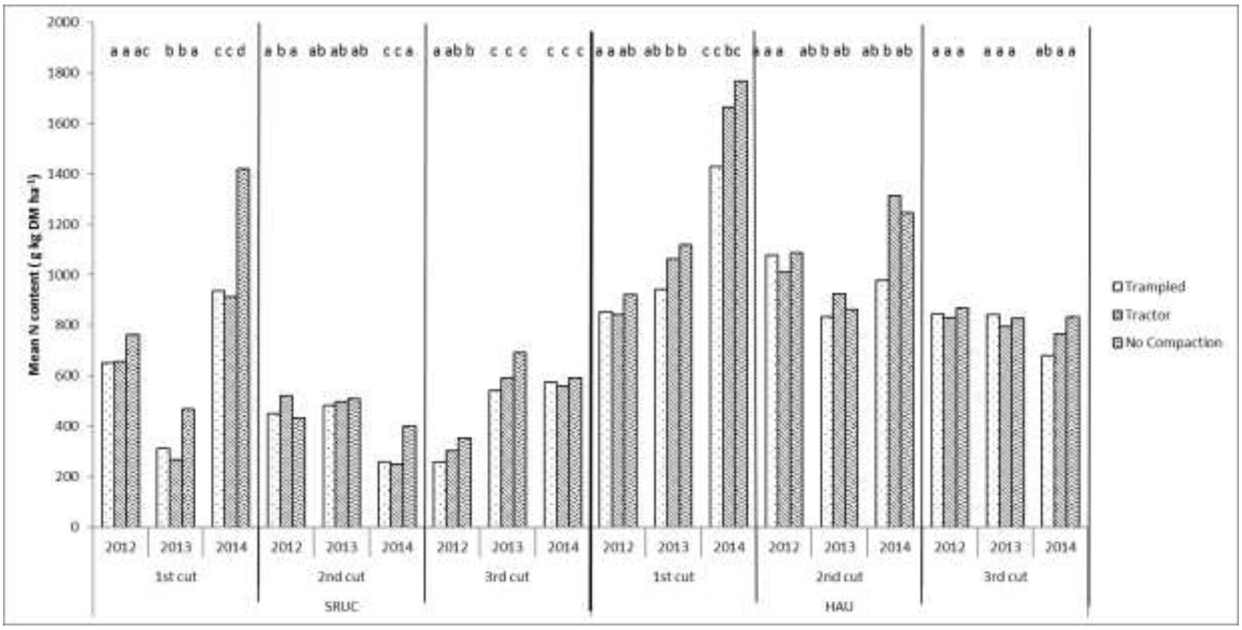
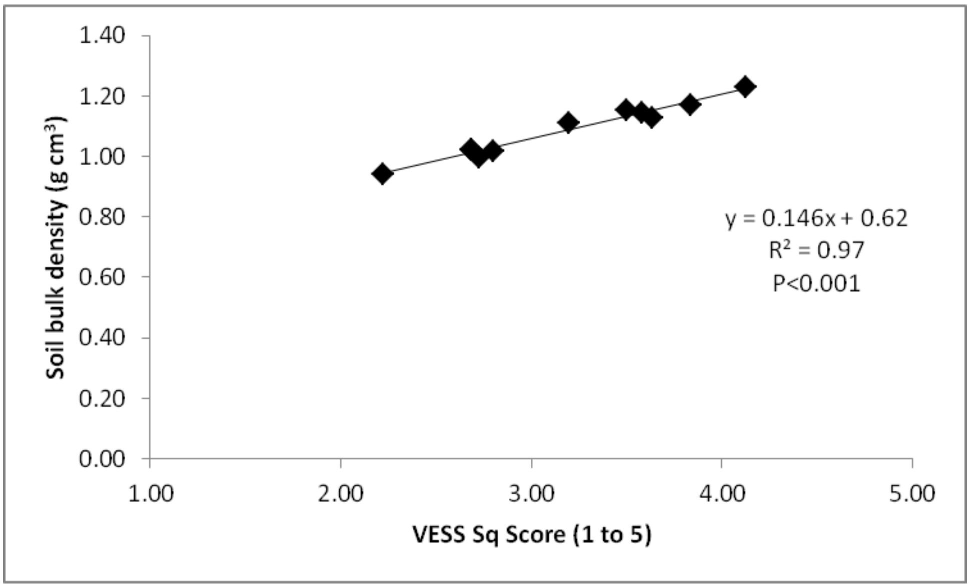
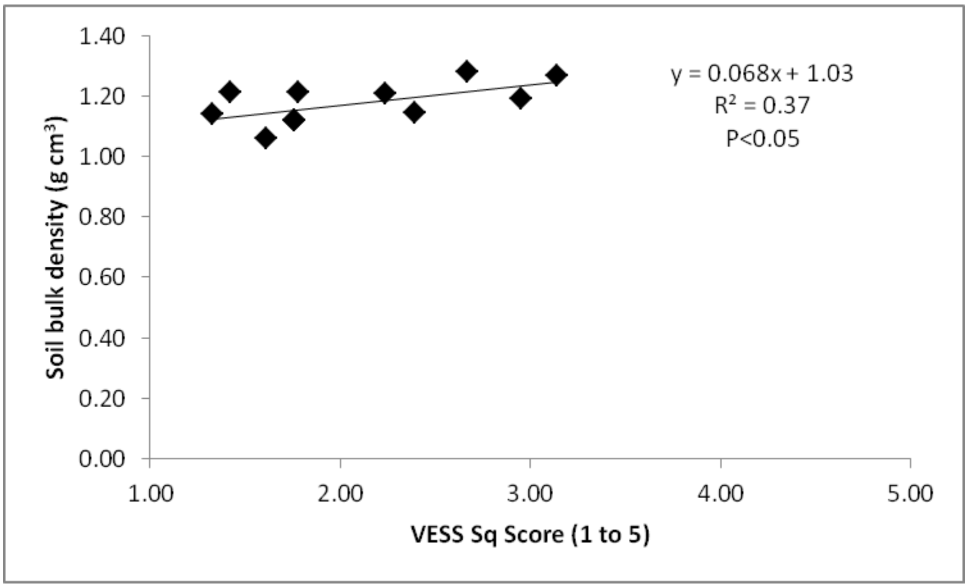


Figure 5. Mean herbage N content (g kg DM ha^{-1}) from the no compaction, trampling and tractor compaction areas for individual and total cuts from SRUC and HAU for the years 2012 to 2014. Letters indicate significant differences (P < 0.05) between means of each silage cut within each year (each site analysed separately).

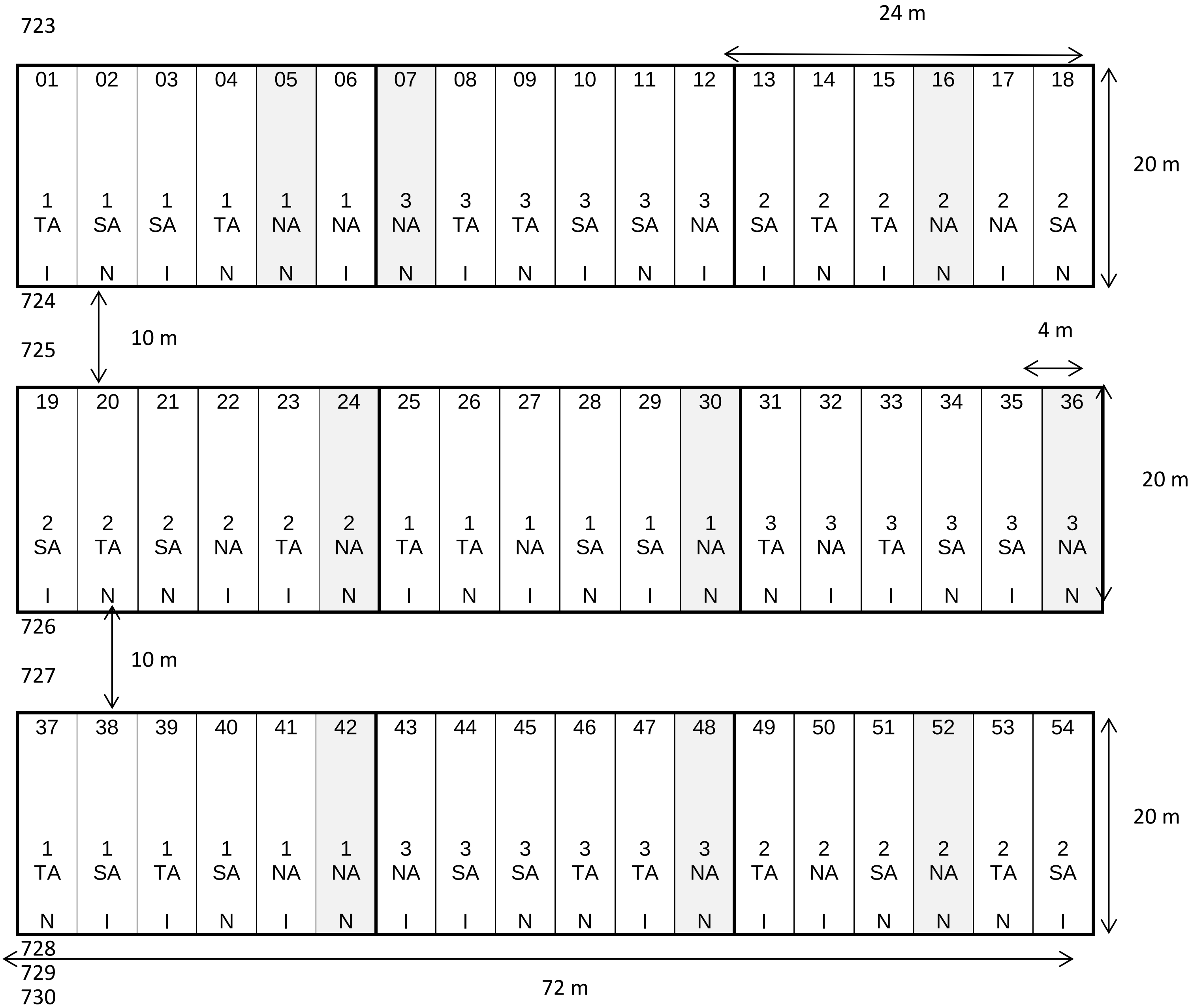


a) SRUC



b) HAU

Figure 6. Regression between the annual mean soil VESS scores (1 (best structure) to 5 (poorest structure)) and the annual mean soil bulk density (g cm^{-3}) at 0 to 10cm depth for all the three treatments (trampling, tractor and no compaction) for 2012, 2013 and 2014, including initial bulk density before the start of the experiment (2011) at a) SRUC – a more clay soil and b) HAU – a sandier soil.



1 = Trampling compaction,
2 = No Compaction
3 = Tractor compaction
TA = Surface aeration, SA = Sward lifter aeration, NA = No aeration
N = No Nitrification inhibitor, I = Nitrification inhibitor

The data used in this study were from the no nitrification inhibitor and no aeration in sub-treatments in each of the replicate blocks.

Supplementary Figure 1. Layout of main treatments and sub-treatments areas of the whole compaction experiment.